Adult height in constitutionally tall stature: accuracy of five different height prediction methods

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Abstract
The accuracy of height predictions at various ages based on five different methods (Tanner-Whitehouse mark I; Tanner-Whitehouse mark II; index of potential height; Bayley-Pinneau; Roche-Wainer-Thissen) was compared at yearly intervals with final height achieved in 32 boys (78 predictions) and 100 girls (227 predictions) with constitutionally tall stature. The boys were initially seen at a mean (SD) chronological age of 12·5 (3) years whereas the mean chronological age in girls was 11·8 (2·1) years.

In tall boys Tanner-Whitehouse mark II gives a good estimation of final height up to the bone age of 13 years with a mean overestimation of 1 cm. The overestimation of final height is higher in the bone age groups 13–14 years (2·7 cm) and 14–15 years (3·4 cm) mainly due to the tall boys with a height greater than 3 SD scores. Up to the bone age of 12 years the final height is massively overestimated by the Bayley-Pinneau method but this method give relatively accurate estimations thereafter. The estimated confidence limits are large (±8 cm) for the two methods up to a bone age of 15 years.

In tall girls the Tanner-Whitehouse mark II method was accurate from bone age nine to 12 years but overestimated final height in the bone age groups 12–13 years and 13–15 years by a mean of 1·8 and 1·4 cm respectively. The Bayley-Pinneau method overestimated final height in the bone age groups 12–14 years whereas the height predictions are accurate thereafter. Up to a bone age of 13 years the estimated confidence limits for the two methods are large, ±7 cm, but tend to improve thereafter.

It is concluded that there is no best or most accurate method for predicting adult height in tall children. There are methods of first choice differing with respect to sex and bone age. In addition, correcting factors may improve their accuracy and correct their tendency to overestimate or underestimate adult height.

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In constitutionally tall children the prediction of adult height is a major parameter for deciding whether or not any treatment should be given. Methods of prediction of adult height are mainly based on growth data from children of normal stature selected more or less at random and followed from infancy to adulthood.[1–6] To date only the Tanner-Whitehouse mark II equation has included samples of tall children.[7] [8] Thus applying standard equations for determining adult height to children with growth disorders may not give accurate results.

If treatment is given an accurate prediction of adult height is an important element in monitoring its influence on growth and skeletal maturation. The evaluation of the extent to which any given treatment has reduced the adult height is based on the difference between the predicted and attained adult height. The criteria for a good prediction method are reasonable accuracy over a large age range, small prediction error, and, if possible, validity for tall and for normal children.

This study was performed to investigate and re-evaluate retrospectively growth data deriving from untreated tall children who were referred to our growth clinic at the paediatric department in Berne and whom we followed up until their adult height was achieved.

Patients and methods
PATIENTS
Thirty two boys and 100 girls entered the study. At referral the mean (SD) age was 12·5 (3) and 11·8 (2·1) years in boys and girls respectively. The mean (SD) bone age ratings were 13·0 (2·6) years in the boys and 12·1 (1·8) years in the girls according to Greulich and Pyle. All the subjects were followed up until adult height was achieved.

The criteria for inclusion were tall stature (greater than two SD scores according to the first Zurich longitudinal study of growth and development[10]) without any disorder explaining the tall stature; the subjects were in good health.

A total of 78 (boys) and 227 (girls) predictions of adult height were performed in the 32 boys and 100 girls at yearly intervals. Adult height was assumed when either two height measurements within six months were equal or the bone age estimated by the method of Greulich and Pyle[9] was ≥18·25 years in boys and ≥16·75 years in girls representing the achievement of 99·8% of their adult height. The remaining growth potential of 0·2% was judged to be within a possible error of measurement.

The subjects were divided into two groups, one consisting of patients with a height of ≥3 SD scores[10] and another of patients with a height >2 SD scores and <3 SD scores.[10] In addition subjects with an accelerated bone age of more than two years were analysed separately and reported whenever the data of the distinct groups were different.

The overall mean adult height in boys was 194·0 (2·6) cm. Only four of the 32 boys initially

had an accelerated bone age of more than two years and their median adult height was 193·7 cm.

The overall mean adult height in girls was 177·3 (2·2) cm. Seventeen of the 100 girls initially showed an accelerated bone age of more than two years and their mean adult height was 174·2 cm. In addition four girls presented a retarded bone age (≥2 years) when they were first seen and reached the mean adult height of 180·6 cm.

HEIGHT MEASUREMENT

All measurements were taken using a Harpenden stadiometer with the technique of gentle upward pressure applied under mastoid processes to stretch the child to maximum stature. Measurements were performed by the staff of the paediatric endocrine clinic and checked by a paediatric endocrinologist. The height data are expressed as SD scores for chronological age using the tables derived from the first Zurich longitudinal study of growth and development.[10] We measured three tall children on three different occasions to define the intra-assay and interassay coefficients of variation. The intra-assay coefficient of variation was 0·08, 0·06, and 0·09% at 164·7, 176·3, and 186·5 cm respectively. The interassay coefficient of variation was 0·29, 0·31, and 0·34% at 164·7, 176·3, and 186·5 cm respectively.

BONE AGE

Radiographs of the hand and wrist were taken and rated according to the methods described by Greulich and Pyle[9] and by Tanner *et al.*[2 7] In this study all the bone ages were analysed by RT.

When using the Greulich and Pyle method[9] the carpal bones are excluded from the estimation of the bone age according the recommendations to Roche *et al*[6] and Lenko.[3]

We determined the radius-ulna-short (RUS) bone score of the Tanner-Whitehouse 2 system (TW2-RUS).[2 7] The total scores of the ratings were not analysed according to the orginal tables based on the Harpenden growth study but according to those of the more recent Zurich longitudinal growth study (TW-ZH).[10]

EQUATIONS OF PREDICTION OF ADULT HEIGHT

Tanner-Whitehouse mark I

This equation is based on three variables namely height, chronological age, and bone age (TW-ZH)[1 2 10] and, in addition, the girls are separated into premenarcheal and postmenarcheal. Taking the midparental height into account a correction factor (one third of the difference of midparental height of the subject and the midparental height of the population (midparental height Zurich=171·3 cm))[10] can be added to the prediction calculated between the bone age of 9 and 14 years and between the bone age of 7 and 13 years in boys and girls respectively.

Tanner-Whitehouse mark II

This revised method replaced the Tanner-Whitehouse mark I equation described in 1975[2] and is based on samples that include tall and short children.[7] This method can be used with a minimum of three variables (chronological age, bone age, height) but additional equations are given when the height velocity or the change in bone age, or both, are known. This can improve the prediction mainly at a bone age of over 8 years in girls and 11 years in boys.[7]

Index of potential height method

This method described by Lenko and coworkers is based on the assumption that the height SD scores for bone age remains constant up to the final height.[3 11] For calculation we used the mean and SD scores of the Zurich longitudinal growth study[10] and the bone age (TW2-RUS) adapted to these norms (TW-ZH).

Bayley-Pinneau equation

This equation is based on bone age estimated by the method of Greulich and Pyle.[9] There are separate tables for normal, retarded (greater than or equal to one year) and accelerated (greater than or equal to one year) bone age. As the Swiss population seems to be retarded by six months compared with the group studied by Greulich and Pyle we used, according to the suggestion by Zachmann, the tables for retarded bone age if the bone age was retarded ≥1·5 years.[12]

Roche-Wainer-Thissen

Recumbent length is required for the Roche-Wainer-Thissen predictions.[5 6] As in our patients only the standing height was available, 1 cm was added to this value for the calculation of adult height prediction.

Results

Predicted adult height minus attained adult height was calculated for each of the five prediction methods. Therefore positive results indicated overestimation whereas negative results indicated underestimation of the predicted adult height by the method applied. The figure shows the mean (SD) values of these differences for each bone age year interval.

BOYS

Tanner-Whitehouse mark I equation

The Tanner-Whitehouse mark I method gave reasonably accurate results up to a bone age of 13 years but tended to slightly overestimate height for a bone age of 13–15 years. Dividing the patients with a bone age between 13 and 15 years into two groups, namely a group with a height SD score between 2 and 3 and a group with height ≥3 SD scores, it became clear that the overestimation in that age group was due to the tall boys (≥3 SD scores) and that the prediction was accurate for the boys with a height between 2 and 3 SD scores. The overestimation of final height in the very tall boys (≥3 SD scores) with a bone age of 13–14 and 14–15 years was 6·2 and 4·5 cm respectively whereas it was only 0·5 and 0·8 cm in the same bone age

groups in boys with a height between 2 and 3 SD scores. In the bone age group ≥16 years the method is of no use. This is highlighted by the fact that some patients were already taller than the predicted adult height at the time of the prediction. Surprisingly the correction factor for midparental height did not improve the results; on the contrary the overestimation in the younger bone age groups was increased (data not shown).
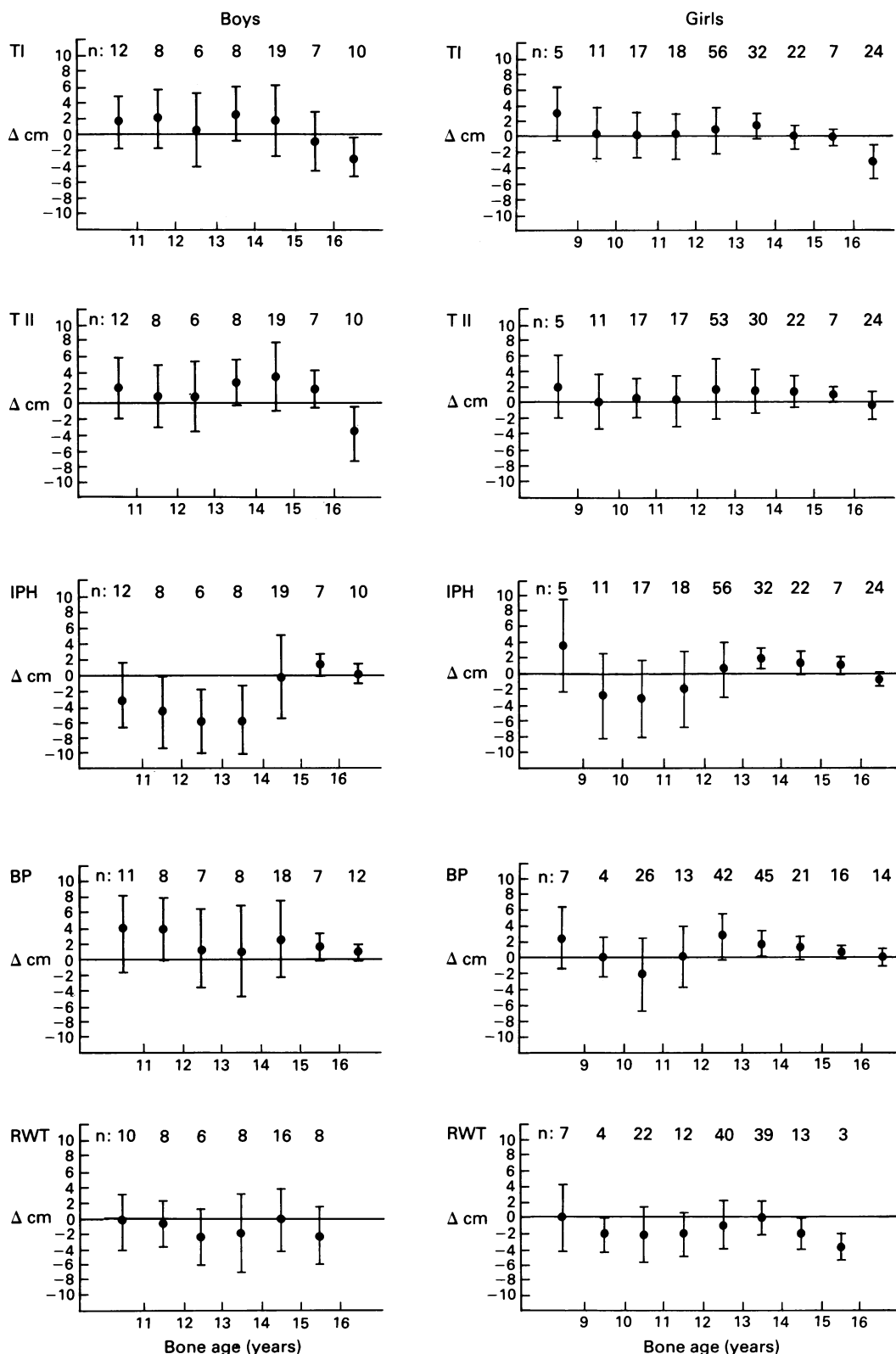
Deviation (Δ, cm) of adult height prediction from actually achieved final height in subjects with constitutionally tall stature. Abbreviations used: T I = Tanner-Whitehouse mark 1; T II = Tanner-Whitehouse mark II; IPH = index of potential height; BP = Bayley-Pinneau; RWT = Roche-Wainer-Thissen. Overall mean (SD) values are shown. Results are presented in bone age groups. The radius, ulna, and short bones method of Tanner et al[7] based on the data of the Zurich longitudinal growth study[10] bone age and the Greulich and Pyle[9] rating were used for the T I, T II, IPH and BP, RWT prediction methods respectively.

Tanner-Whitehouse mark II equation

In general the same results were found as for the Tanner-Whitehouse mark I method. The Tanner-Whitehouse mark II method tended to overestimate slightly more in the bone age group 14–15 years. On 12 occasions we were able to introduce height velocity and increment of bone age as a variable in the equation. This did not improve the prediction compared with that derived from the three variables equation (data not shown). Similar to the Tanner-Whitehouse mark I method the mean overestimation in the bone age groups of 13–14 and 14–15 years was more pronounced (4·5 and 5·9 cm respectively) in the tall boys (height ≥3 SD scores) than in boys with a height between 2 and 3 SD scores (1·6 and 2·5 cm respectively). Up to the bone age of 15 years the estimated confidence limits of prediction are ±8 cm for the Tanner-Whitehouse mark I and Tanner-Whitehouse mark II estimation methods.

Index of potential height method

A marked underestimation was seen up to a bone age of 16 years. The results thereafter were accurate, however.

Bayley-Pinneau equation

This method overestimated the prediction with estimated confidence limits of prediction of ±10 cm up to the bone age of 15 years. In the older bone age groups the method was accurate with confidence limits tending to decrease.

Roche-Wainer-Thissen equation

This method gave a reasonably accurate prediction up to the bone age of 12 years followed by a slight underestimation during the bone age period of 12–14 years which gave way again to accurate prediction values for a bone age of 14–16 years.

GIRLS

Tanner-Whitehouse mark I equation

Although the method was reasonably accurate in girls with a bone age between 9 and 16 years it overestimated the adult height in the group with a bone age of less than 9 years and tended to underestimate in the group with a bone age >16 years in such a way that some girls were already taller than the predicted adult height. Notably girls who presented a bone age that was accelerated compared with their chronological age (greater than or equal to two years) showed an overestimation of adult height in the age groups 13–14 years of 3·1 cm in contrast to 1·2 cm in girls without bone age acceleration. In addition, as was seen in boys, the correction factor for midparental height made the adult height prediction even worse.

Tanner-Whitehouse mark II equation

In general the same results were found as when using the Tanner-Whitehouse mark I equation. Eighty seven predictions were performed using the additional variables (height velocity or increment of bone age, or both). A small but not significant improvement in accuracy of the prediction of adult height compared with the predictions obtained using the Tanner-Whitehouse mark I method was found (data not shown).

Index of potential height method

This method was inaccurate and of no use in the bone age groups less than 12 years. Between a bone age of 12 and 16 years a slight overestimation was found.

Bayley-Pinneau equation

The adult height was overestimated in the bone age groups less than 9 years. In the bone age group 10–11 years the overall underestimation was mainly due to the girls with an accelerated bone age of more than two years. The underestimation in these girls with an accelerated bone age was 5·0 cm in contrast to the 1·3 cm in girls with a non-accelerated bone age. There was a tendency to overestimate in the bone age groups 12–13 years. The method gave relatively accurate results thereafter.

Roche-Wainer-Thissen equation

Although this method generally underestimated the adult height it could be useful for the bone age groups less than 9 years and 12–14 years.

The estimated confidence limits for all height prediction mentioned are ±7 cm up to a bone age of 13 years and ±4 cm thereafter, presenting a tendency for improvement.

Tables 1 and 2 give the prediction method recommended for boys and girls together with the correction factors that have to be added to the calculated predicted adult height.

Discussion

Tall boys and an even larger number of tall girls are referred to paediatric endocrine clinics because information is requested regarding future growth potential. Comparison of actual and parental height, estimation of bone maturation with appropriate standards, and prediction

Table 1 Recommended height prediction method for tall boys. Mean deviations (cm) of predicted from actually achieved final height are given as correction factors to subtract or add from the calculated adult height obtained using the various prediction methods

Prediction method*	Bone age (years)						
	<11	11–12	12–13	13–14	14–15	15–16	>16
T I: all >2 SDS	—	—	0·6	2·6	1·8	—	—
T I: 2 SDS–3 SDS	—	—	—	0·5	0·8	—	—
T I: ≥3 SDS	—	—	—	6·2	4·5	—	—
T II: all >2 SDS	1·9	0·9	0·9	2·7	3·4	—	—
T II: 2 SDS–3 SDS	—	—	—	1·6	2·5	—	—
T II: ≥3 SDS	—	—	—	4·5	5·9	—	—
IPH all >2 SDS	—	—	—	—	−0·33	1·4	0·0
BP all >2 SDS	—	—	1·3	1·0	2·5	1·5	0·7
RWT all >2 SDS	−0·2	−0·5	—	—	0·2	—	—
Estimated confidence limits (2 SD) for all methods (cm)	8	8	8	8	8	2·5	1·5

*The radius, ulna, and short bones method of Tanner *et al*[7] based on data from the Zurich longitudinal growth study[10] was used for the Tanner-Whitehouse mark I, Tanner-Whitehouse mark II, and Index of potential height methods and the Greulich and Pyle[9] rating for the Bayley-Pinneau and Roche-Wainer-Thissen methods. Abbreviations: T I=Tanner-Whitehouse mark I; T II=Tanner-Whitehouse mark II; IPH=index of potential height; BP=Bayley-Pinneau; RWT=Roche-Wainer-Thissen; SDS=standard deviation score.

Table 2 Recommended prediction method for tall girls. Mean deviations (cm) of predicted from actually achieved final height are given as correction factors to subtract or add from the calculated adult height obtained using the various prediction methods

Prediction method*	Bone age (years)								
	<9	9–10	10–11	11–12	12–13	13–14	14–15	15–16	>16
T I: all >2 SDS	—	0·4	0·2	0·1	0·6	1·4	−0·2	−0·3	—
T I: 2 SDS–3 SDS	—	—	−1·3	—	—	—	—	—	—
T I: ≥3 SDS	—	—	1·9	—	—	—	—	—	—
T II: all >2 SDS	—	0·2	0·5	0·2	1·8	1·4	1·4	0·9	—
IPH: all >2 SDS	—	—	—	—	0·7	1·9	1·4	1·0	—
BP: all >2 SDS	—	—	—	0·1	—	—	1·3	0·9	0·3
RWT: >2 SDS	0·0	—	—	—	−0·8	0·1	—	—	—
Estimated confidence limits (2 SD) for all methods (cm)	7	7	7	7	7	4·0	3·0	2·0	1·0

*The radius, ulna, and short bones method of Tanner et al[7] based on data from the Zurich longitudinal growth study[10] was used for the Tanner-Whitehouse mark I, Tanner-Whitehouse mark II, and index of potential height methods and the Greulich and Pyle[9] rating for the Bayley-Pinneau and Roche-Wainer-Thissen methods. Abbreviations: T I=Tanner-Whitehouse mark I; T II=Tanner-Whitehouse mark II; IPH=index of potential height; BP=Bayley-Pinneau; RWT=Roche-Wainer-Thissen; SDS=standard deviation score.

of adult height are important tools for deciding whether or not any treatment is indicated.

Height predictions are calculated using any of the methods described here. We have to bear in mind, however, that these equations have been developed for normal children, not for children with growth disorders.[1-6] Only the height prediction method reported by Tanner and coworkers based on a large number of normal children had included samples of tall children.[7-8] Applying these methods of predicting adult height to series of tall children until ultimate adult height is reached allows a comparative evaluation of these different equations.

We analysed the validity, variability, and accuracy of the five commonly used methods of height prediction in 32 boys and 100 girls. This study clearly shows that there are different systematic errors (error between mean values of predicted height and adult height achieved) in the equations applied for predicting adult height depending on sex and on bone age at the time when the prediction was performed. It should be emphasised that there is no best or most accurate method; each method has its advantages and disadvantages under specific circumstances. Thus it is important for clinicians and investigators using height predictions to evaluate the effect of treatment to know the tendency of each method to underestimate or overestimate adult height. We suggest that the equation should be selected according to sex and actual bone age of the subject and should take into account the mean difference between predicted height and adult height achieved (systematic error) as a correction factor to add or subtract from the calculated adult height (tables 1 and 2). This procedure undoubtedly increases the accuracy of the prediction made.

Brämswig et al compared height predictions with ultimate adult height in boys with untreated constitutionally tall stature and found similar systematic errors by using Tanner-Whitehouse mark I, Bayley-Pinneau, and Roche-Wainer-Thissen methods of prediction of adult height.[13] In contrast Zachmann et al reported excellent results in predicting adult height with the Tanner-Whitehouse mark I, Bayley-Pinneau, and Roche-Wainer-Thissen methods.[14] Unfortunately boys and girls were not separately reported and therefore no direct comparison

with our results is possible.[14] As adult height predictions have been rarely documented in a large number of untreated constitutionally tall girls our data have to be compared with control data derived from studies on the effect of oestrogen treatment in tall girls.[5 14-20] These data are not consistent, however. Although some workers described an overall overestimation of the adult height using the Bayley-Pinneau method[15 16 18 20] others reported accurate results applying the same method,[17 19] which only agrees with our data found for the bone age groups 12–15 years. Furthermore John and Schellong[20] and Sorgo et al[18] described in tall girls with a mean bone age of 13·5 years accurate height predictions using the Tanner-Whitehouse mark I method and we found an overestimation for exactly that age group. In addition Zachmann et al found an improvement in the accuracy of the Tanner-Whitehouse mark I method when the correction factor for midparental height was added.[14] In contrast our results and those of Sorgo et al[18] did not support the conclusion that a correction factor for midparental height improved the accuracy of the predictions of adult height.

It is of importance to note that all prediction methods used in our study had in addition to a systematic error a large relative error (SD of mean values of the prediction method used) in predicting adult height up to a bone age of 13 years in girls and 15 years in boys. In other words an accurate prediction is not possible until the peak height velocity has passed. There are two main reasons for this observation, which not only occurs in tall but also in normal children and children with short stature. First, the bone age, the basic variable of any prediction method, is not a well defined measurement and is dependent on human assessment.[21 22] Like any other measurement, the bone age rating is subject to an interobserver (comparability) and an intraobserver (replicability) error.[22] The smallest differences in the bone age rating therefore result in a considerable difference in adult height prediction when methods that rely heavily on the bone age rating, such as the Bayley-Pinneau[4] and index of potential height methods[3 11] are used. Furthermore using the Greulich and Pyle atlas it is noteworthy that for girls the radiographs depicting the age standard

11 and 12 years are similar.[9] Second, puberty and its growth spurt are dynamic processes that are not consistent. In addition the height gain during the pubertal growth spurt is variable and by no means concordant with the bone age advancement. Thus in consulting with patients the large confidence limits of the predictions must be discussed and it is wise not to give an exact value for the adult height to be achieved but rather the possible range of prediction.

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